

Part 1: Radioactivity

1. You manage to acquire a dangerous sample of radioactive polonium.
- a. According to Wikipedia¹, polonium “has 27 known isotopes, all of which are radioactive.” What does it mean to say that polonium has more than one “isotope”? Include in your response a sketch that helps explain your point – the sketch need only be suggestive of the underlying concept, not numerically precise.

An atomic element, like polonium, is defined by the number of protons in its nucleus – the atomic number. Polonium has an atomic number of 84, so there are 84 protons in its nucleus. A neutral polonium atom therefore has 84 electrons. This number defines its *chemical* properties.

What differs between *isotopes* of polonium is the number of *neutrons* in the nucleus. Different isotopes have different numbers of neutrons. Since neutrons have mass, different isotopes weigh slightly different amounts. But they still have the same chemical properties because the number of electrons is the same.

Student sketches will vary, but probably will include drawings of the nuclei of two different atoms that have the **SAME** number of protons, but **DIFFERENT** numbers of neutrons.

- b. Again, according to Wikipedia, “²¹⁰Po is an alpha emitter that has a half-life of 138.376 days; it decays directly to [a] stable daughter isotope.” (You’ll recall that an alpha particle is a helium nucleus.) Write down the decay equation that shows the radioactive decay of ²¹⁰Po, and describe the element that is created through this radioactive decay.

$^{210}\text{Po} \Rightarrow ^{206}\text{Pb} + ^4\text{He}$... this decay produces lead, which is stable (non-radioactive).

- c. Suppose your sample consists of 4 grams of ²¹⁰Po. How long would you have to wait until your sample is reduced, through radioactive decay, to only 1 gram? Express your answer in days. Show your work.

You would have to wait $2 \times (138.376) = 276.752$ days for the sample to halve in size twice.

- d. Alexander Litvinenko, a former member of the Soviet and Russian security services (FSB & KGB), was poisoned in London in 2006 with ²¹⁰Po and died within three weeks². In fact, his tea cup was poisoned. Suppose you wanted to avoid exposure to radiation from the tea cup by moving from a distance of 1 m to a distance of 4 m away from the cup. According to the **inverse-square law**, how many times safer will you be at this new distance? Select one:

no safer

twice as safe

four times safer

eight times safer

sixteen times safer

sixty-four times safer

¹ <http://en.wikipedia.org/wiki/Polonium>

² http://en.wikipedia.org/wiki/Alexander_Litvinenko_poisoning

2. A physicist might say that we should be thankful for naturally occurring radioactivity. Can you give one or more examples of situations in which radioactivity might not be a bad thing?

Naturally occurring radioactivity in the Earth's interior keeps it heating – this allows for volcanic eruptions which occasionally produce global cooling (if enough ash is spewed out). This radioactivity also drives mutations on Earth, which (together with the process of natural selection) has allowed evolution of species – without this evolutionary flexibility, life might no longer exist, and we certainly wouldn't be here. Radioactive sources are also used for medical imaging, in smoke detectors (!), and in other useful devices. Students answers may vary.

3. Recall that so-called “beta-particles” were later discovered to be the particle we call electrons. One radioactive element, ^{137}Cs (cesium), beta-decays with a half life of 30 years.

- a. What element is produced when ^{137}Cs beta-decays, and which isotope of this element is produced? Include in your answer the appropriate decay equation.

$^{137}\text{Cs} \Rightarrow ^{137}\text{Ba} + e^- + \nu$ the element barium is produced, with an atomic weight of 137

- b. You have a sample of 100 g of ^{137}Cs . After 90 years, how much of your sample would still remain? Show your work.

Since 90 years is three half-lives, the sample would be $100\text{ g} \Rightarrow 50\text{ g} \Rightarrow 25\text{ g} \Rightarrow \mathbf{12.5\text{ g}}$.

4. What, ultimately, is the *cause* of nuclear decay? Include in your answer a description of the four fundamental forces of nature, and what role (if any) each plays in radioactive decay.

Electrical repulsion between the positively charged protons in the nucleus pushes the nucleus apart. Attraction due to the short-range strong nuclear force holds the nucleus together. Nuclear decay occurs when the repulsion is too much for the attraction.

A different kind of decay (beta decay) occurs when a neutron spontaneously converts into a proton, electron, and neutrino. One can think of a neutron as being “held together” by the weak nuclear force.

The final force not mentioned here, gravity, plays no role in nuclear processes.

5. Suppose, during the explosion of a nuclear bomb, 0.010 kg of uranium is converted *directly* into energy. Using Einstein's famous equation, calculate the amount of energy, in Joules, that is released as gamma-rays from this explosion.

$$E = mc^2 = (0.010\text{ kg})(3 \times 10^8\text{ m/s})^2 = 9 \times 10^{14}\text{ J}$$

Part 2: Energy Conservation

1. Describe in words the difference between *kinetic* energy and *potential* energy. Use examples, and include at least one sketch. Explain as you would to a 5th grader – someone who doesn't have the benefit you have of extensive practice with the topic.

When something is moving, we say that it has kinetic energy. Big heavy things moving fast have the most kinetic energy. Small, light things moving slowly have less kinetic energy. If something is standing still, it has no kinetic energy, no matter how big it is.

Potential energy is "stored" energy. Imagine you are holding up a book with a string. If someone were to cut the string, the book would fall and gain kinetic energy. This energy came from somewhere: we say it was "stored" in the book when it was held up by the string. Big, heavy things that are held high in the air have a lot of potential energy; small, light things close to the ground have less potential energy. If something is sitting on the ground it has no potential energy.

Sketches will vary enormously by student.

2. Suppose you are crane operator and you're lifting a very heavy chunk of concrete. Right now, the concrete is up in the air and so has a potential energy of 10,000 J (but no kinetic energy).
 - a. You use your crane to begin lifting the chunk of concrete even higher. In lifting the concrete, you do 15,000 J of work on it. How much total energy does the concrete have now?

$$E_{\text{tot}} = E_{\text{before}} + W = 10,000 \text{ J} + 15,000 \text{ J} = 25,000 \text{ J}$$

- b. If, in doing that 15,000 J of work, you only lifted the chunk of concrete a distance of 1.5 m, how much *force* did you apply? Don't forget to include proper units in your answer!

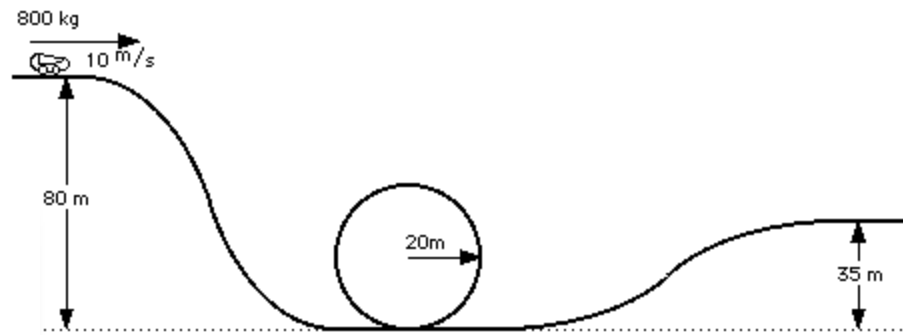
$$W = 15,000 \text{ J} = \text{force} \times \text{distance} = \text{force} \times 1.5 \text{ m} \quad \text{therefore} \quad \text{force} = 15,000 \text{ J} / 1.5 \text{ m} = 10000 \text{ N.}$$

- c. The chunk of concrete has a mass of 150 kg. The cable on your crane breaks! How *fast* is the chunk of concrete traveling when it hits the ground?

Before falling, its total energy is 25,000 J. When it hits the ground, *all* of this energy is converted into kinetic energy. So $K = 25,000 \text{ J} = \frac{1}{2}mv^2 = \frac{1}{2}(150 \text{ kg})v^2$... solve this to get $v = 18.3 \text{ m/s}$.

3. A train is racing along a horizontal track with 100 MJ (megajoules) of kinetic energy and no potential energy. Superman is going to push on the train to bring it to a stop before it runs over his sweetie. How much work (in Joules) will Superman have to do to bring the train to a stop?

100 MJ of work. (Yes, this problem is that easy.)



4. For this problem, consider the roller-coaster diagram shown above. (We will neglect friction – all energy in this problem will be in either kinetic or potential form.)
- a. The roller coaster begins at a height of 80 m with a speed of 10 m/s towards the right. Its mass is 800 kg. What is the initial *kinetic* energy of the coaster?

$$K = \frac{1}{2}mv^2 = \frac{1}{2}(800 \text{ kg})(10 \text{ m/s})^2 = 40,000 \text{ J}$$

- b. What is the initial *potential* energy of the coaster?

$$U = mgh = (800 \text{ kg})(10 \text{ m/s}^2)(80 \text{ m}) = 640,000 \text{ J}$$

- c. What is the initial *total* energy of the coaster?

$$E_{\text{tot}} = K + U = 40,000 \text{ J} + 640,000 \text{ J} = 680,000 \text{ J}$$

- d. Calculate the speed of the coaster when it is ...

- i. ... at the top of the loop (note the loop has a radius of 20 m).

At the top of the loop, it has potential energy $U = (800 \text{ kg})(10 \text{ m/s}^2)(40 \text{ m}) = 320,000 \text{ J}$. Since its total energy is *still* 680,000 J, this means it has $K = 680,000 \text{ J} - 320,000 \text{ J} = 360,000 \text{ J}$.

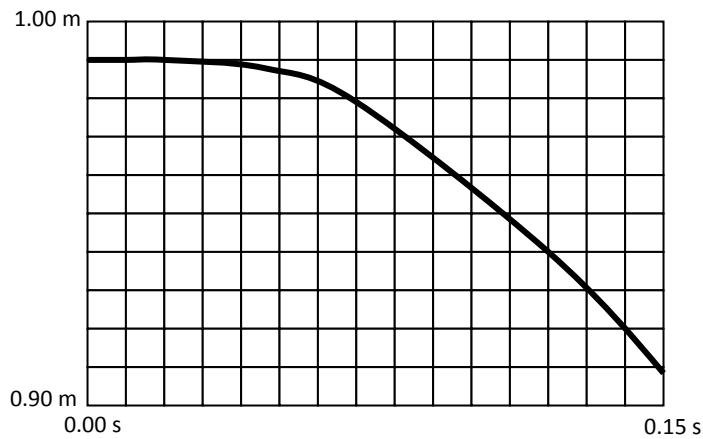
$$360,000 \text{ J} = K = \frac{1}{2}mv^2 = \frac{1}{2}(800 \text{ kg})v^2 \quad \dots \text{ solve this to get } v = 30 \text{ m/s.}$$

- ii. ... at the horizontal part of the track at the end (at height 35 m).

At this point at the end, it has potential energy $U = (800 \text{ kg})(10 \text{ m/s}^2)(35 \text{ m}) = 280,000 \text{ J}$. Since its total energy is *still* 680,000 J, this means it has $K = 680,000 \text{ J} - 280,000 \text{ J} = 400,000 \text{ J}$.

$$400,000 \text{ J} = K = \frac{1}{2}mv^2 = \frac{1}{2}(800 \text{ kg})v^2 \quad \dots \text{ solve this to get } v = 31.6 \text{ m/s.}$$

5. You carried out an experiment in our lab using the Lab Pro data acquisition system and the Logger Pro computer program. You dropped a cart of known mass (0.25 kg) onto a sonic range finder, producing the following position vs. time and velocity vs. time graphs:



Select two points in time (of your choosing) from the graph above and determine whether the total energy was *conserved* in this experiment. If there was a discrepancy between the energy at two points in time, calculate the % difference. (Note the formula for this is available on your blue equation sheet.) Be clear in your explanation & calculations below.

Student answers will vary. Basically, the idea is to choose one point in time (say, $t = 0.00$ s) and calculate $K = \frac{1}{2}mv^2$ and $U = mgh$ at that point in time. Then choose a second point in time (say, $t = 0.15$ s) and recalculate K and U at that point in time. The sum of $K + U$ should be the same at both points. They should at least be close. The student would then calculate the % difference between the two values of TOTAL energy to see how accurate the prediction of energy conservation is measured in this experiment.